Acoustic Analysis of Crying Signal in Infants with Disabling Hearing Impairment[☆]

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Summary: Objective. Crying is a multimodal, dynamic behavior and the first way to communicate. Early identification of hearing impairment is critical for prevention of speech and language disorders. The present study aimed to assess the acoustic features of infant's cry signals to find possible differences between two groups including hearing-impaired (HI) infants and normal hearing (NH) control.

Methods. The data were collected from 34 (17 HI, 17 NH) infants under 2 months of age. Recording of the infant cry signals was collected during the examination of the Babinski reflex and was subsequently submitted for acoustic analysis. The total duration of the recording for each infant was approximately 30 seconds. The acoustical features included fundamental frequency (F_0), formants (F_1, F_2, and F_3), intensity, jitter, shimmer, ratios of F_2/F_1 and F_3/F_1, ratio of harmonic to noise, and voice break. The recording device was an Olympus ws-321M voice recorder with 44,100 Hz sampling frequency in the stereo form. Praat analysis software (version 27, 3, 5) was used to analyze the crying signals. The data were then statistically analyzed using SPSS version 21.

Results. Acoustic analysis of the crying signals showed that HI infants have lower intensity and higher F_0 and voice break than NH infants. However, the other differences were not statistically significant.

Conclusion. The results of the present study demonstrated that the acoustic components including F_0, intensity, and voice break may be used as indices to discriminate HI infants from NH infants under 2 months of age. These findings can be increased our knowledge concerning the functional mechanisms of the vocal organ in HI and NH infants.

Key Words: Crying signal–Hearing loss–Hearing impairment–Infant–Acoustic-screening.

INTRODUCTION

Bilateral and permanent hearing impairment is estimated to be between 1.2 and 5.7 per 1000 live births.[1] This rate is reported to be 3 per 1000 among Iranian infants.[2] Approximately half a billion people affected by disabling hearing impairment which makes up about 6.8% of the world's population. These numbers are substantially very high and point to the growing importance of hearing impairment and global hearing health care.[3] The typical consequences of this condition include significant delays in language development and academic achievement,[1] because the brain of hearing-impaired (HI) infants does not receive any auditory feedback from the speech organ. Assessment of hearing in children and early identification of hearing impairment have been considered crucial because early diagnosis of hearing impairment results in better outcomes in speech, language development, and educational achievement.[4]

Studies show if the auditory feedback is missing, the created sound by HI individuals may be acoustically different from the normal hearing (NH) individuals,[5] so the analysis of sounds is an objective method for evaluating the baby's hearing without his/her cooperation. Due to the limitations in other methods, an analysis of infants' sounds and vocalizations seems to be an alternative method for assessing children's hearing.

Vocalization and crying are two types of sounds produced by infants. Studies of infant vocalizations have shown that vocalizations develop in an ordered sequence of stages between birth and the first words. Regardless of the linguistic community in which words are learned, babies begin by communicative crying, cooing, and then producing reduplicated consonant-vowel (CV) syllables, also known as canonical babbling, and then nonreduplicated CV, also known as variegated babbling with sentence-like intonational patterns. Then they express first pseudo-words, single syllable words, and multisyllabic words.[4,6,7] As the vocabulary grows, the frequency of babbling declines until the age of around 18-20 months, when it ceases completely. Some researchers have reported strong similarities in the babbling of NH and HI infants, while others have reported the opposite.[4] For example, Eilers and Oller,[8] Moeller et al,[9] and Schramm et al[10] reported that HI infants are significantly delayed at the onset of canonical babbling. Stoel-Gammon and Otomo[4] reported HI infants as a group who produced a

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lower proportion of CV strings with true consonants prior to month 18. Therefore, the timetable and the nature of babbling in HI infant are not yet well understood.

Vocalization in infants up to 12 months of age has been shown to be dependent on auditory feedback.[11,12] But on the one hand, unlike crying, vocalization such as cooing and babbling does not exist in the first days of birth and it is crucial to detect the hearing impairment in the first days of birth, and on the other hand, there are contradictory opinions about the difference in vocalization between the two groups. As a result, we will study the differences in crying between the two groups in this study.

Crying signals are important to be considered by researchers because crying is the primary method of communication and the acoustic analysis of the produced sound in crying is an index of function of the whole auditory system. Production of sounds is a direct result of the laryngeal function shaped by the resonating cavities including the oral cavity.[4,13] Möller and Schönweiler[11] identified longer cry durations and more complex melody contours in infants with HI in comparison to NH infants. Jones found a higher fundamental frequency (F_0) in HI infants compared to NH infants.[14] Wermke et al[15] found a lower amount of acoustic energy with higher harmonics in HI infants. Möller and Schönweiler[11] reported that cries of HI infants have less energy in the upper frequency bands and the second formant (F_2) is lower in HI infants than NH infants. In addition, cries of HI infants are longer than their NH counterparts. Melodic analyses indicated a higher complexity of cries for HI infants than NH infants.[11] Therefore, it seems that the characteristics of HI infant cries are different from those of NH infants and might be used as a criterion for an early diagnosis of hearing impairment. The aim of previous studies was to use infant cries as a diagnostic tool for certain diseases.

Although the existing strategies of newborn hearing screening have a high reliability, the author's research team finds it essential to try to work out a new, cheaper, simple and reliable screening method, which would give a new potential approach to the early detection of hearing impairment. Regarding to Wermke et al,[15] an analysis of the acoustic parameters of infant cries might offer a noninvasive tool for the assessment of vocal productions. Accordingly we were targeted to create a new hearing screening tool which be able to analysis infant's crying signals based on acoustical features of infant's cry. The purpose of the present study was therefore to investigate a comparison of the various acoustic characteristics of cry signals between HI and NH infants group. To our knowledge, few studies have been performed to investigate acoustical features of HI infant cries in literatures yet. The findings of this investigation create a new horizon to present a new hearing screening method based on the acoustic differences between the cries of normal infants and HI infants in the future.

MATERIALS AND METHOD

Subjects

In total, the data were collected from 34 full-term infants including 17 (8 girls and 9 boys) HI infants (M = 1.76 month, standard deviation = ± 0.66) with mean birth weight of 2319.21 ± 334 g and 17 (8 girls and 9 boys) NH infants (M = 1.34 month, standard deviation = ±0.54) with mean birth weight of 2761.21 ± 435 g as a control group enrolled in the study who referred to the ENT and Head and Neck Research Center of Rasoul-e-Akram Hospital (Tehran, Iran) from July 2015 to May 2016. We included only babies who had severe to profound hearing impairment confirmed by the auditory brain stem responses (ABR) and the distortion product otoacoustic emission (DPOAE) tests. The recordings were made in three hospitals of Iran University of Medical Sciences, Tehran, Iran. None of the subjects had a history of anatomical abnormalities or observational neurological illness according to the examiner's observations and parental reports. None of them had preterm births. The results of otoacoustic emission (OAE) and ABR diagnostic tests were summarized in two groups of the HI and the NH control infants (for details see Table 1).

The parents were given a written consent form. The study was approved by the Ethical Committee of the ENT and Head & Neck Research Center, Iran University of Medical Sciences, Tehran, Iran.

TABLE 1.
Mean Values and Standard Deviations for Auditory Diagnostic Tests in Two Groups of the HI and NH Infants

Hearing results		HI infant (N = 17)		NH infant (N = 17)	
		Mean	SD	Mean	SD
Click ABR estimated threshold (dB nHL)	Left ear	No response	-	22.05	3.09
	Right ear	No response	-	21.47	2.34
Tone burst ABR at 500 Hz estimated threshold (dB nHL)	Left ear	No response	-	25.88	1.96
	Right ear	No response	-	26.17	2.18
DPOAE (dB)	Left ear	No response	-	15.23	4.67
	Right ear	No response	-	17.11	4.24

Abbreviations: dB nHL, dB for normal hearing level; SD, standard deviation.

Acoustic analyses procedures

The baby was placed in the mother's arms. The distance between the microphone and the mouth of the infant was 20 cm. None of the infants were hungry or felt sleepy during the recording. The infant cries were collected during the examination of the Babinski reflex. For the appearance of the reflex, the lateral side of the sole of the foot was stimulated by a blunt instrument.

The recording device was an Olympus ws-321M voice recorder with 44,100 Hz sampling frequency in the stereo form. Finally, all the recorded sounds were saved onto a personal computer as separate wave (.wav) files. The overall duration of the recordings was approximately 30 seconds for each infant. All the sound recordings were made in a quiet and sound-proof room in the hospital.

The author used Praat analysis software (version 27, 3, 5)[16] for all the crying analysis steps. Praat analysis software investigated the sound signals based on the cries, which were shown as a sequence of segments repeatedly. We used the broadband analysis and the linear predictive coding to convert the acoustic waves to spectral data. These methods are excellent to view the temporal structure of the sounds and to see the vowel formants.[16] First, the whole cry signal was separated to the crying segments because preprocessing is necessary to eliminate the technical defects of the recording (eg, silence, background noise, and coughing) and to find the important sections of the crying signal. Each segment of crying has a start point and an end point. For detecting the vocal signals, we used the method applied by Zhang et al.[17] Their technique is based on observing the spectrum of the crying signal in certain times. If harmonic spectral components are found, the investigated signal is a part of a cry segment. For this purpose, we asked three speech and language pathologists to observe and listen to the crying signals, and to separate the critical segments of the crying signals based on Zhang's idea. Five to six cries were gathered from each infant, which summed up to 187 cries: 85 cries from the healthy infants and 102 from the HI group. Second, the acoustic features of the selected segments were extracted including the spectrum, F_0, intensity, jitter, shimmer, formants (F_1, F_2, and F3), ratios of F_2/F_1 and F_3/F_1, ratio of noise to harmonic and harmonic to noise (HNR), and voice break.

Hearing assessment procedures

We did not include any baby with abnormal initial OAE and then normal ABR or vice versa. As we already mentioned, the aim of current study was assessed the acoustic characteristics of infant crying signals to find possible differences between two groups including HI infants and NH controls. In this regard, we included only babies with severe to profound hearing impairment confirmed by the ABR and the DPOAEs tests. ABR and DPOAE were administered to confirm the hearing impaired in the group of HI infants as well as the NH status in the NH control group. The stimuli for ABR and DPOAEs were generated using Bio-logic Navigator Pro electrophysiological system (Bio-logic Systems Corp., a Natus Company, Mundelein, IL). The ABR test was measured in response to a click, and for wave V in response to a 500 Hz tone burst. The infants were laid on a bed in an acoustically and electrically shielded room. The responses were recorded with a vertical montage of four-disk Ag-AgCl electrodes (noninverting on the vertex [Cz], grounded on the forehead, and inverting the electrodes on each mastoid). Contact impedance indicators for the disk electrodes were less than 2 kΩ, which was maintained at a level lower than 5 kΩ.

We applied sweep tones in frequency over a ($2f_1$-f_2) range of 500−4000 Hz for DPOAEs that enhance response levels (eg, L_1-L_2 = 0 dB; f_2/f_1 = 1.22; L_1, L_2 = 70, 70 dB of sound pressure level [dB SPL]). The special infant probe assembly was employed. The data were screened to include a minimal signal-to-noise ratio of 3 dB before the analyses. Data points with the noise floor of above 0 dB SPL were also rejected. The responses greater than 6 dB SPL above the background noise (signal-to-noise ratio) at four frequencies (0.5, 1, 2, and 4 kHz) were regarded as sounds regarded within a healthy (ie, normal hearing and functioning) cochlea.

Statistical analyses

The Kolmogorov−Smirnov test was performed to investigate the normal distribution of the samples. The distribution of the samples was normal. Descriptive statistics were used to explain the results of auditory diagnostic tests and the demographics of the population-gestational age, birth weight, gender stratification in two groups of HI and NH infants. An independent sample t test was used to compare the different variables in the two-matched groups (NH infants and HI infants). Results with $P \leq 0.05$ were declared significant.

RESULTS

The results of the DPOAE and ABR tests are reported in Table 1. Absolute latencies were measured for waves I, III, and V at 80, 60, 40, and 25 dB for normal hearing level in response to a click and for wave V at 80, 60, 40, and 25 dB for normal hearing level in response to a 500 Hz tone burst.

Table 2 summarizes the results of the t test comparisons, with significant differences highlighted. The mean value of F_0 in the HI infants was higher in comparison to the NH infants and the differences in F_0 was statistically significant ($t_{23.7} = -0.289$, $P = 0.000$). The mean value of F_1 in the HI infants was lower compared to the NH infants, but the differences between the two groups were not statistically significant ($t_{32} = 1.698$, $P = 0.09$). Moreover, the mean value of the F_2/F_1 ratio was lower in the HI infants than in the NH infants but the differences were not statistically significant ($t_{32} = -1.373$, $P = 0.17$). The mean value of intensity was lower in the HI infants than in the NH infants and the differences of intensity were statistically significant ($t_{32} = 2.555$, $P = 0.01$). Moreover, it was found that the mean value of HNR was lower in HI infants than in NH infants but the difference was not statistically significant

TABLE 2.
Results of Independent Sample *t* Tests and the Means and Standard Deviations (in the Brackets) of Acoustic Features in NH Infants and HI Infant Cries

Acoustic features	NH infants	HI infants	*t* value	*P* value
	Mean (SD)	Mean (SD)		
F_0, Hz	348.67 (51.84)	388.86 (2.6)	−2.849	0.00
F_1, Hz	1086.33 (127.55)	1002.67 (158.16)	1.698	0.09
F_2, Hz	2033.84 (289.04)	2014.46 (270.82)	0.202	0.84
F_3, Hz	2941.65 (537.15)	2827.02 (303.76)	0.766	0.44
F_2/F_1, Hz	1.88 (0.30)	2.03 (0.32)	−1.373	0.17
F_3/F_1, Hz	2.72 (0.61)	2.86 (0.43)	−0.774	0.44
Intensity, dB	82.49 (3.22)	79.34 (3.91)	2.555	0.01
Shimmer, %	5.68 (3.18)	5.96 (2.53)	−0.282	0.78
Jitter, %	0.89 (1.10)	0.89 (0.73)	0.013	0.98
Voice break	0.64 (0.93)	2.23 (2.30)	−2.633	0.01
HNR mean, Hz	14.05 (4.70)	13.10 (4.28)	0.615	0. 54
Duration, s	2.34 (1.17)	1.87 (0.72)	1.383	0.17

Abbreviation: SD, standard deviation.

($t_{32}=0.615$, $P=0.54$). Compared to the NH infants, the mean value of the voice breaks was higher in the HI infants and the differences of the voice breaks were statistically significant ($t_{32}=-2.633$, $P=0.01$). The mean value of the duration of one signal of crying was lower in the HI infants than in the NH infants but these differences were not statistically significant ($t_{32}=1.383$, $P=0.17$).

The overall duration of the recordings for each infant was approximately 30 seconds. A selected crying signal (about 6 seconds out of 30 seconds) is presented in Figure 1 as a sample, which shows the waveform and the spectrograph of the crying signal (about 6 seconds) in an NH infant and an HI infant with 28 days of age. Also, one segment of the selected crying signal (one crying signal) in the two groups is presented in Figure 1. The figure shows that the number of signals in the HI infant during the 6 seconds recording of the crying signal was higher than in the NH infant and the total duration of the one crying signal in the HI infant was shorter than in the NH infant.

DISCUSSION

In general, the results of the present study on infant crying have demonstrated that some of the acoustic features including F_0, intensity, and voice break were statistically different between the NH infants and HI infants. These can be used as a suitable acoustic measure to investigate sound production characteristics and conditions of potential language developmental risks during infancy. The findings of the present study can be utilized to define the important acoustic components in differentiating between HI infants and NH infants. We believe that by developing a diagnostic tool, we will create new possibilities for infants who suffer from birth defects or undetectable diseases, develop a faster treatment, and protect them from health threats. Moreover, future efforts to evaluate the crying differences between normal infants and other infants with various disorders especially congenital HI may be a worthwhile enterprise.

In the current study, the specification of voice break data revealed significant differences in the crying signal of the two groups. Voice break is referred to as the sudden and unintended changes in the pitch and the quality of voice.[18] The mean voice break was higher in the HI infants than in the NH infants. The HI population has excessive effortful vocalization because the auditory feedback is missing. Consequently, the tension of the larynx in the HI infants was higher in comparison to the NH infants and probably the increase of tension results in an increase in the voice break.[19]

The other objective of our study was to determine the difference between F_0 in the crying signal of the two groups of infants. We found that the HI infants had a significantly greater mean F_0 than the NH infants. The fundamental frequency is vibration of the vocal folds.[20] Hamzavi et al,[21] Wermke et al,[15] and Etz et al[12] showed the mean F_0 is greater in HI individuals than NH individuals. Varallyay and Benyó et al[22] reported the same results. Laryngeal muscle tension/contraction contributes to controlling F_0.[23] As already mentioned, the tension of the laryngeal muscle in the HI infants was higher in comparison to the NH infants and probably the increase of tension results in an increase in F_0.[19] Also, the auditory feedback has an important role in controlling F_0. Lack of auditory feedback in profound HI babies can probably influence on greater F_0 in HI infants compared to NH infants.[24]

Another finding of the present study showed that the mean intensity of the crying signals in HI infants was significantly lower in comparison to the NH infants. It seems that the auditory feedback is one of the important factors in controlling loudness.[25] The brain of the HI population does not have any auditory feedback. It seems that these infants usually use the proprioceptive sensory to precept their

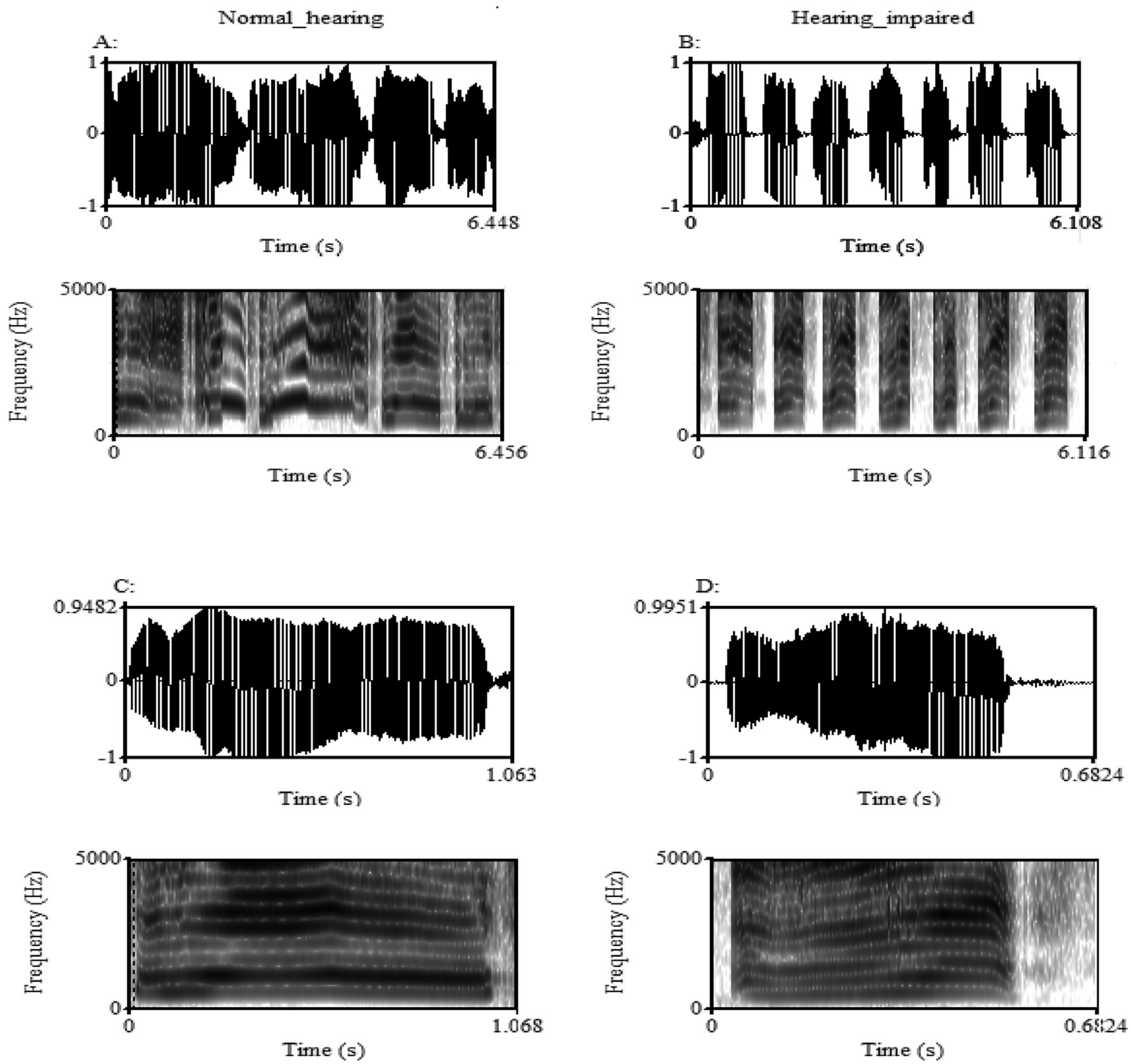

FIGURE 1. **A.** Selected crying signal from an NH infant at 28 days of age. The waveform was shown at the top and the spectrogram was shown at the bottom. **B.** Selected crying signal concerning an HI infant at 28 days of age. The crying signal was broken more in the HI infant than in the NH infant. The number of crying signals increased in the HI infant during the 6 seconds of crying. **C.** The one crying signal in the NH infant. The waveform was shown at the top and the spectrogram at the bottom. **D.** The one crying signal in the HI infant. The duration of the one crying signal was shorter in the HI infant than the NH infant.

vocalization. This probably results in additional activation and tension in the larynx. The tension of the larynx can result in an increase in the subglottic pressure and a decrease in the airflow in the vocal tract.[26] As a consequence, it is expected that the intensity of crying be lower in HI infants. The results were in line with Etz et al's[12] study in which the intensity significantly decreased in HI infants compared to NH and cleft palate infants.

Another finding in our study showed that the mean value of F_1 and F_2 was smaller in the HI infants but the difference between NH infants and HI infants was not statistically significant. The structure of formants (F_1, F_2, and F_3) is the most important physical property of vowels since the quality of a vowel depends on these formants.[27] F_1 is related to tongue height, F_2 is related to tongue backing, and F_3 is related to lip spreading.[28,29] Consistent with our study, Nicolaidis et al[30] reported smaller values for F_1 and Etz et al[12] found smaller values for F_2 in HI infants. Development of vowels usually occur between 0 and 6 months after birth;[31] however, the samples of this study were in the age range of 0−2 months. Therefore, F_1 and F_2 features may indicate greater changes after the age of 2 months especially in the HI infants. Also, the small sample size probably influenced our nonsignificant results.

Additionally, the index of HNR was lower in the HI infants than in NH infants. Nevertheless, the difference was not statistically significant between the two groups. The ratio is a measure of harmonic energy to noise energy in the signal and an objective and quantitative index to evaluate the degree of hoarseness and harsh voice quality. If the degree of the judged hoarseness increases, there will be more and more noise; therefore, HNR will decrease.[32,33] Other features that can be used to evaluate the hoarseness include measurements of voice frequency (jitter) and amplitude (shimmer) perturbation. When jitter increases, the noise can be enhanced and then the harmonic index reduces.[33] The higher F_0 is associated with the higher jitter. In the present study, the increase of F_0 in the HI infants did not result in any change in the jitter and the shimmer measurements. As a result, it seems that the collection of the acoustic features such as HNR, jitter, and shimmer are determinative of the degree of hoarseness. In agreement with our study, Etz et al[12] found higher mean values for microvariability of vocal fold functions (especially shimmer) in HI infants compared to NH infants. However, more investigations are needed to be carried out on the hoarseness of crying in HI infants with a larger sample size.

The investigation of cry duration in the two groups demonstrated a shorter duration for the HI infants compared to the NH infants. Nonetheless, the result was not statistically significant. These findings were inconsistent with the results of Möller and Schönweiler[11] and Etz and et al.[12] They reported a longer duration of crying in HI infants than NH infants. Perhaps, the reason was that instead of investigating the whole cry signal, we investigated the duration of a cry segment in the two groups of infants in our study.

The whole auditory system is involved during the crying baby to control the quality of the produced voice. In this way the acoustic analysis of crying signals produced by an infant can be useful to check the function of auditory system integrity. Also, the volume, the pitch, and the tone color is changing during baby's cry. The logic of the current study was based on the question whether or not a sample of a baby's cry signal can reflect of congenital hearing impairment. We also intended to know that whether or not infant voice analysis test can be used for primary health care system purposes. So, further investigations with a large sample size should be determined to consider validity of the test as a screening tool. These voice signals will be analyzed by a specific voice analyzer software to compare the results. We are looking for a sensitive and specific screening method using signal processing knowledge and analysis of such signals through the preprocessing, feature extraction, classification, and design of proper user medium. This idea has been sought to implement our suggested system in the newborn hearing screening. The authors of this study emphasis to performed other studies to clarify the role of congenital hearing impairment degrees (mild, moderate, severe, and profound hearing impairments) and the types of hearing impairment on cry voices. The characteristics of crying signal for each infant will be compared with the crying signal characteristics of normal infants of the same age group. Therefore the infants will be classified into two groups of pass (normal) or refer (need to more diagnostic tests).

However, according to the present results the analysis of the infant's cry characteristics can get potentially valuable information to early identify deafness before 1 month yields. The information from this study is not sufficient for using crying as a screening tool. There is a critical concern regarding the sensitivity and specificity of the cry analysis test as well as overall reproducibility of the test, particularly in primary care settings. If the sensitivity and specificity would be acceptable then we would be able to implement in a large population of infants. Since acoustic analysis of crying signal in newborns and infants is easily performed, so this test can be potentially considered as a newborn hearing screening instead or combined with OAE/ABR screening tests. In screening approach, all neonates would be classified as "pass" for normal or "refer" for the case has some probity of abnormality to arrange more clinical diagnostic considerations.

Our data suggest that the characteristics of F_0, intensity, and voice break may be the most important acoustic features to demonstrate the difference between the crying of HI and NH infants younger than 2 months. Nonetheless, other factors such as F_2/F_1, F_1, and HNR can also be important to separate HI infants and NH infants. Previous studies did not investigate all of these factors. Therefore, the neurophysiological bases of infant crying still remain unknown. Further research is needed to demonstrate the effects of these acoustic features especially in infants older than two months old, because the morphology and the histology of vocal folds may change anatomically and functionally during the maturation period, especially in the respiratory and neurophysiological control mechanisms.[34,35]

CONCLUSIONS

According to the results of this study, it seems that some cry acoustical features of infants including F_0, intensity, and voice break are different between the two groups of HI and NH infants. These cry acoustical features may be utilized to a developed tool for early identification of hearing impairments among infants. A logical continuation of this study is to include larger infant HI populations with different hearing statuses, including normal, mild, moderate, and severe hearing impairment. All of the infants in this study had severe to profound hearing impairments approved by physiologic and electrophysiological tests. Therefore, these subjects represent the severe to profound hearing impairment population, which constitutes a fraction of hearing impairment. The correlation between hearing thresholds and the observed cry signal alterations suggests that future studies should examine the effect of congenital hearing impairment on crying signals. Also further studies should be conducted in primary care settings to explore the influence of components of the testing procedure to optimize test sensitivity and to promote standardization of the testing procedure. Besides, it is necessary to investigate the acoustic characteristics of crying in the different age groups of infants from 0 month to 1 year old to developmentally identify the differences between their crying signals. These longitudinal studies should be addressed in subsequent studies.

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SUPPLEMENTARY MATERIALS

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jvoice.2018.05.016.

REFERENCES

1. Yoshinaga-Itano C, Sedey AL, Coulter DK, et al. Language of early- and later-identified children with hearing loss; *Pediatrics*. 1998;102:1161–1171. https://doi.org/10.1542/peds.102.5.1161.
2. Firoozbakht M, Mahmoudian S, Alaeddini F, et al. Community-based newborn hearing screening programme for early detection of permanent hearing loss in Iran: an eight-year cross-sectional study from 2005 to 2012; *J Med Screening*. 2014;21:10–17. https://doi.org/10.1177/0969141314522992.
3. Wilson BS, Tucci DL, Merson MH, et al. Global hearing health care: new findings and perspectives; *Lancet* 2017;. https://doi.org/10.1016/S0140-6736(17)31073-5.
4. Stoel-Gammon C, Otomo K. Babbling development of hearing-impaired and normally hearing subjects; *J Speech Hear Disord*. 1986;51:33–41. https://doi.org/10.1044/jshd.5101.33.
5. Perkell JS, Guenther FH, Lane H, et al. A theory of speech motor control and supporting data from speakers with normal hearing and with profound hearing loss; *J Phonetics*. 2000;28:233–272. https://doi.org/10.1006/jpho.2000.0116.
6. Hoff E. Lexical development: learning words. *Language Development*. Cengage Learning; 2005:183–219.
7. Várallyay G. Future prospects of the application of the infant cry in the medicine. *Period Polytech Electr Eng*. 2006;50:47–62.
8. Eilers RE, Oller DK. Infant vocalizations and the early diagnosis of severe hearing impairment; *J Pediatrics*. 1994;124:199–203. https://doi.org/10.1016/S0022-3476(94)70303-5.
9. Moeller MP, Hoover B, Putman C, et al. Vocalizations of infants with hearing loss compared with infants with normal hearing: part I−phonetic development; *Ear Hearing*. 2007;28:605–627. https://doi.org/10.1097/AUD.0b013e31812564ab.
10. Schramm B, Keilmann A, Brachmaier J. Canonical babbling and early hearing and language development of normal hearing children and children with cochlear implants; *Cochlear Implants Int*. 2010;11:375–378. https://doi.org/10.1179/146701010X12671177990073.
11. Möller S, Schönweiler R. Analysis of infant cries for the early detection of hearing impairment1; *Speech Commun*. 1999;28:175–193. https://doi.org/10.1016/S0167-6393(99)00016-3.
12. Etz T, Reetz H, Wegener C. A classification model for infant cries with hearing impairment and unilateral cleft lip and palate; *Folia Phoniatr Logop*. 2012;64:254–261. https://doi.org/10.1159/000343994.
13. Zeifman DM. An ethological analysis of human infant crying: answering Tinbergen's four questions; *Dev Psychobiol*. 2001;39:265–285. https://doi.org/10.1002/dev.1005.
14. Jones MC. Diagnostic implications of acoustic cry features; *J Commun Disord*. 1971;4:310–316. https://doi.org/10.1016/0021-9924(71)90010-4.
15. Wermke K, Hauser C, Komposch G, et al. Spectral analysis of prespeech sounds (spontaneous cries) in infants with unilateral cleft lip and palate (UCLP): a pilot study; *Cleft Palate-Craniofacial J*. 2002;39:285–294. https://doi.org/10.1597/1545-1569_2002_039_0285_saopss_2.0.co_2.
16. Boersma P, Weenink D. *Praat−a system for doing phonetics by computer [Computer Software]*. The Netherlands: Institute of Phonetic Sciences, University of Amsterdam; 2003.
17. Zhang T, Kuo C-CJ. Audio content analysis for online audiovisual data segmentation and classification; *IEEE Trans Speech Audio Process*. 2001;9:441–457. https://doi.org/10.1109/89.917689.
18. Munoz J, Mendoza E, Fresneda M, et al. Acoustic and perceptual indicators of normal and pathological voice; *Folia Phoniatr Logop*. 2003;55:102–114. https://doi.org/10.1159/000070092.
19. Lee E-K, Son Y-I. Muscle tension dysphonia in children: voice characteristics and outcome of voice therapy; *Int J Pediatric Otorhinolaryngol*. 2005;69:911–917. https://doi.org/10.1016/j.ijporl.2005.01.030.
20. Evans S, Neave N, Wakelin D. Relationships between vocal characteristics and body size and shape in human males: an evolutionary explanation for a deep male voice; *Biol Psychol*. 2006;72:160–163. https://doi.org/10.1016/j.biopsycho.2005.09.003.
21. Hamzavi J, Deutsche W, Baumgartner WD, et al. Short-term effect of auditory feedback on fundamental frequency after cochlear implantation. *Audiology*. 2000;39:102–105.
22. Várallyay G. The melody of crying; *Int J Pediatric Otorhinolaryngol*. 2007;71:1699–1708. https://doi.org/10.1016/j.ijporl.2007.07.005.
23. Honda K, Hirai H, Masaki S, et al. Role of vertical larynx movement and cervical lordosis in F0 control; *Language Speech*. 1999;42:401–411. https://doi.org/10.1177/00238309990420040301.
24. Burnett TA, Senner JE, Larson CR. Voice F0 responses to pitch-shifted auditory feedback: a preliminary study; *J Voice*. 1997;11:202–211. https://doi.org/10.1016/S0892-1997(97)80079-3.
25. Larson CR, Sun J, Hain TC. Effects of simultaneous perturbations of voice pitch and loudness feedback on voice F0 and amplitude control; *J Acoust Soc Am*. 2007;121:2862–2872. https://doi.org/10.1121/1.2715657.
26. Liang F-Y, Yang J-S, Mei X-S, et al. The vocal aerodynamic change in female patients with muscular tension dysphonia after voice training; *J Voice*. 2014;28. 393.e397−393.e310; https://doi.org/10.1016/j.jvoice.2013.11.010.
27. Nicolaidis K, Sfakianaki A. Acoustic characteristics of vowels produced by Greek intelligible speakers with profound hearing impairment II: the influence of stress and context; *Int J Speech-Language Pathol*. 2016;18:388–401. https://doi.org/10.3109/17549507.2016.1151934.
28. Waaramaa T, Alku P, Laukkanen A-M. The role of F3 in the vocal expression of emotions; *Logop Phoniatr Vocol*. 2006;31:153–156. https://doi.org/10.1080/14015430500456739.
29. Sussman HM. Acoustic correlates of the front/back vowel distinction: a comparison of transition onset versus "steady state"; *J Acoust Soc Am*. 1990;88:87–96. https://doi.org/10.1121/1.399848.
30. Nicolaidis K, Sfakiannaki A. An acoustic analysis of vowels produced by Greek speakers with hearing impairment. *ICPhS XVI, Saarbrücken*. 1969–1972.
31. Hoff E. Phonological development: learning the sound of language. *Language Development*. Cengage Learning; 2013:109–136.
32. Yumoto E, Gould WJ, Baer T. Harmonics−to−noise ratio as an index of the degree of hoarseness; *J Acoust Soc Am*. 1982;71:1544–1550. https://doi.org/10.1121/1.387808.
33. Yumoto E, Sasaki Y, Okamura H. Harmonics-to-noise ratio and psychophysical measurement of the degree of hoarseness; *J Speech, Language, Hear Res*. 1984;27:2–6. https://doi.org/10.1044/jshr.2701.02.
34. Sieck GC, Fournier M, Blanco C. Diaphragm muscle fatigue resistance during postnatal development; *J Appl Physiol*. 1991;71:458–464. https://doi.org/10.1152/jappl.1991.71.2.458.
35. Newman JD. Neural circuits underlying crying and cry responding in mammals; *Behav Brain Res*. 2007;182:155–165. https://doi.org/10.1016/j.bbr.2007.02.011.